A low-frequency hybrid energy harvester with high output performance

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Abstract. Harvesting energy from ambient environment as a power source has attracted a wide attention now. However, it meets with difficulties of achieving high output performance under low excitation frequency. This paper presents a low-frequency hybrid energy harvester with high output performance based on frequency-up-conversion (FUC) approach. Under the strike of electromagnetic harvesting suspension structure, the PVDF cantilevers can operate at their resonant frequency with larger amplitude. The power output and energy conversion efficiency can be improved significantly at low frequency excitation. For an excitation acceleration of 0.5g, the peak voltage output of electromagnetic part can reach to 1.9 V at driving frequency of 23.6 Hz. In addition, the peak voltage of PVDF cantilever increases from 30 mV to 3 V and the working frequency increase from 23.6 Hz to 60.6 Hz by using FUC approach.

1. Introduction

Vibration energy harvesting attracts a wide attention at present for the application on power supply of microelectronics [1-2]. Many vibration energy harvesting devices based on different conversion mechanisms have been proposed [3-5]. In order to achieve high power efficiency, the natural frequency of an energy harvester should be designed to match with the environment vibration source [6-7]. Research shows that frequencies of most vibration sources in the environment are below 200 Hz [8]. The existing harvesters with high energy output always work at high frequency while devices with low working frequency cannot achieve high power output. It becomes a great challenge to design an energy harvester with high energy output and low working frequency. The key solutions are to improve the energy output density and energy conversion efficiency of devices. Wang's group has developed a variety of triboelectric nanogenerators based on vertical contact-separation model, sliding model, and single-electrode model. The highest energy density is up to 45 mW/cm^3 [9-11]. Tang et al proposed a low-frequency vibration piezoelectric MEMS generator by bonding bulk PZT on an SOI structure [12]. The power density is 28.9 mW/cm^3 under the excitation acceleration of 1g. To obtain higher energy conversion efficiency at low frequency, Kulah and Najafi [13] presented an electromagnetic power generator based on FUC system, which can scavenge energy efficiently from low-frequency external vibrations. Liu et al [14] also proposed two piezoelectric energy harvesting systems based on FUC mechanism. The peak power density can reach to 159.4 μW/cm^3 at a low operating frequency of 25 Hz.


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In this study, we demonstrated a low-frequency hybrid energy harvester with high output performance based on FUC approach. Under an external excitation, the electromagnetic harvesting suspension structure is able to impact with four high-frequency PVDF harvesting cantilevers with large amplitude, the output performance of PVDF cantilevers can be improved significantly. At the same time, the electric voltage across the coil is also generated from the electromagnetic part.

2. Device and working principle

The schematic diagram of the fabricated harvesting device is shown in figure 1, which consists of electromagnetic and piezoelectric parts with general dimensions of 7 cm×7 cm×4.3 cm. The main components are winding coil, permanent magnet, spring structure beam, excitation piece and four pieces of PVDF cantilevers. The spring structure beam is processed from a circular copper with the thickness of 0.8 mm. A permanent magnet with the diameter of 40 mm and height of 4 mm is attached on the one side of the spring structure beam, while excitation piece is attached on the other side. The winding coil of 0.09 mm in diameter and 200 m in total length is tightly wound surrounding the hollow cylinder. Four commercial PVDF cantilevers with the size of 41 mm×16 mm are distributed below the excitation piece. The photograph of hybrid energy harvester is shown in figure 2(a) and the components are shown in figure 2(b), (c), (d) and (e).

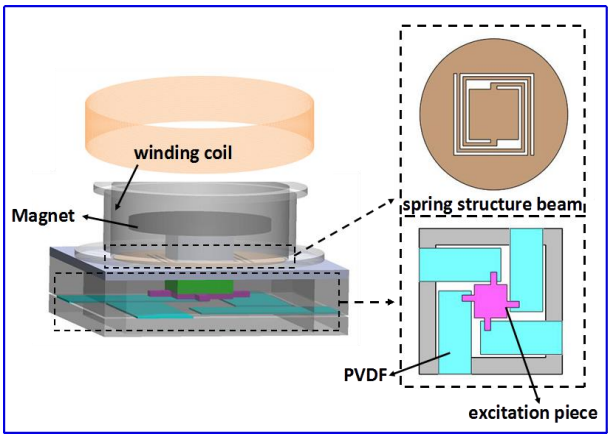


Figure 1. Schematic drawing of the hybrid energy harvester.

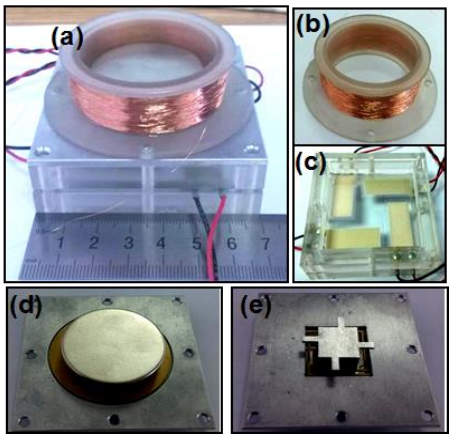


Figure 2. Photograph of the harvester and its components.

Figure 3 shows the sectional view of the device and the vibration state of inner components. As the harvesting device is driven by an external excitation, both the electromagnetic and piezoelectric parts generate electrical power. For electromagnetic part, the working principle is based on law of electromagnetic induction. Under the external excitation, the spring structure beam will drive the permanent magnet to vibrate at vertical direction. Magnetic flux crossing the coil changes and electrical voltage is generated.

As to piezoelectric part, the commercial PVDF cantilevers with high resonant frequency are chosen as energy harvester for the reason that the generated power is theoretically proportional to the cube of the operation frequency [15]. However, the output performances of high-frequency PVDF cantilevers are relatively low under the low driving frequency. In order to improve the power output, an excitation piece connecting with spring is used to impact against the PVDF harvesting cantilevers. As shown in figure 3(b), the excitation piece vibrates in response to external excitation until it impacts with PVDF cantilevers located beneath. As the excitation piece separates from PVDF cantilevers as shown in figure 3(c), the released cantilevers will vibrate damply at their higher resonant frequency with large amplitude before the next impact occurs. Therefore, the AC voltage output of PVDF cantilevers can be improved by an order of magnitude.

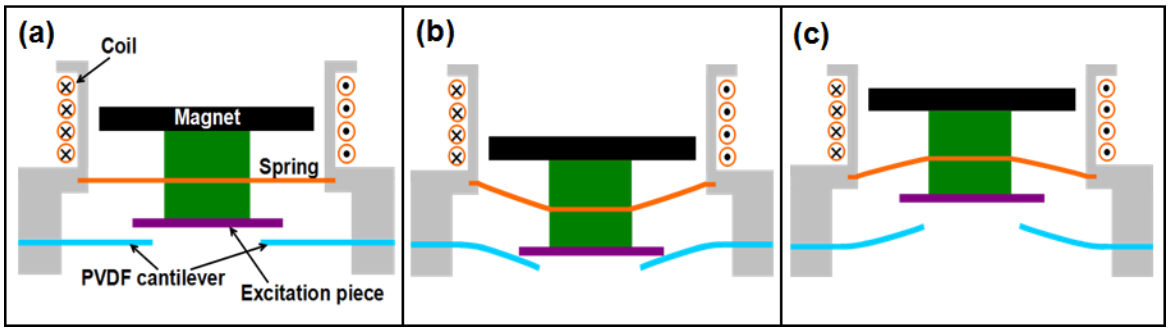


Figure 3. Illustration of the operation process of the energy harvester

3. Experiment and results

The assembled device is tested by a vibration control system. The experimental result in figure 4(a) shows the output performance of electromagnetic harvesting part in frequency domain. For an excitation acceleration of 0.5g, the peak voltage output across the coil can reach to 1.9 V at resonant frequency of 23.6 Hz. The voltage waveform of the electromagnetic part in time domain is also shown in the inset figure of figure 4(a). The output performance of PVDF harvesting cantilever in frequency domain is shown in figure 4(b). The maximum output voltage of a single PVDF cantilever can reach to 3 V with the strike of excitation piece at the excitation frequency of 23.6 Hz (point **A**). After that, the second peak voltage output of 0.9 V will occur when it reaches to the resonant frequency of 60.6 Hz (point **B**). The inset figure of figure 4(b) shows the voltage waveform of the PVDF harvesting cantilever at resonant frequency of 60.6 Hz at point **B**. Figure 5 shows the voltage waveforms of PVDF with (point **A**) and without the strike of excitation piece at excitation frequency of 23.6 Hz. The peak voltage increases from 30 mV to 3 V and the working frequency increase from 23.6 Hz to 60.6 Hz under the strike of excitation piece. It can be easy to get a conclusion that the output performance of PVDF harvesting cantilever is improved significantly by using FUC approach. In addition, there are four cantilevers integrated in the energy harvester and the electromagnetic part will also generate electrical power. Therefore, the total output performance of this device is quite high.

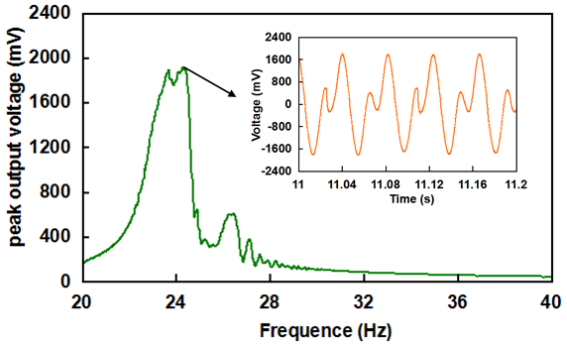


Figure 4. (a) The voltage output of the electromagnetic harvesting structure in frequency and time domain at 0.5g.

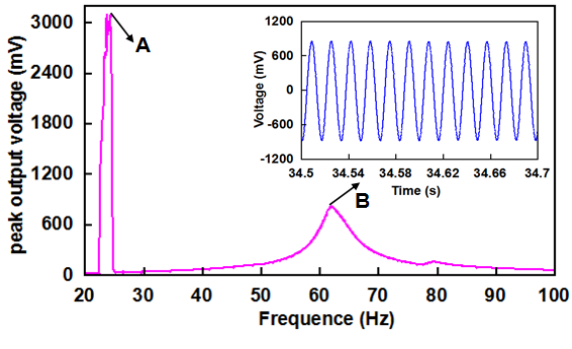


Figure 4. (b) The voltage output of the PVDF harvesting cantilever in frequency and time domain (point **B**) at 0.5g.

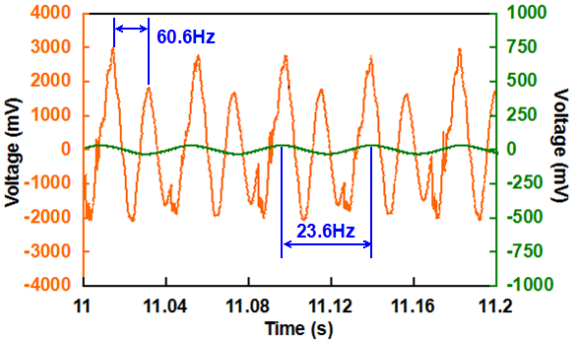


Figure 5. The voltage waveforms of PVDF cantilever with and without the strike of excitation piece at excitation frequency of 23.6 Hz

4. Conclusion

In this paper, we proposed a hybrid energy harvester based on FUC approach, which can achieve high output performance under low excitation frequency. An excitation piece is designed to impact with PVDF cantilevers, resulting in a significant improvement of electrical output. For an excitation acceleration of 0.5g, the peak voltage output of electromagnetic and piezoelectric parts can reach to 1.9 V and 3 V, respectively, at the driving frequency of 23.6 Hz.

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